Indian J Phys **75B** (6), 497-503 (2001)

I J P B
an international journal

Noise temperature and attenuation due to clouds in microwave and millimetrewave frequency bands for satellite borne systems

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Received [illegible] August 2001, accepted [illegible] September 2001

Abstract : Atmospheric noise temperature in the microwave and millimetrewave bands is a useful parameter to determine the cloud characteristics as well as total water vapour content in the medium. Attenuation of the radiowave operating from 10 GHz to 100 GHz is also useful to study the clouds and rain effects [S D Slobin *Radio Sci* **17** 1443 (1982)]. Noise temperature and attenuation due to cloud have been derived at various frequencies. It has been found that 15 GHz is the most suitable frequency for studies of cloud properties. The effects of water content in the clouds and height (thickness) of the cloud on cloud noise temperature have been deduced. The analytical studies have revealed that some of the frequencies are altogether unsuitable for cloud studies, particularly the effect of clouds is minimum on the frequencies from 55 GHz to 60 GHz.

Keywords : Attenuation, cloud, signal to noise

PACS No. : 94.10.-s

1. Introduction

The total attenuation is the sum of the individual contributions of the major constituents of the atmosphere such as oxygen, water vapour, rain and the clouds. Microwave radiation at frequencies below 100 GHz and cloud particles smaller than 100 μm, the effect of scattering is small and absorption is the only contribution to attenuation. The absorption medium itself radiates power into a radio receiver and contributes to the total system noise temperature. Other contributions to the system noise temperature are cosmic background, the ground and the receiver. Noise temperature effect of water vapour content of the atmosphere was studied by Westwater [1], Gaitrud *et al* [2], Sen *et al* [3] at 22.24 GHz for its estimation. Smith *et al* [4] presented the effect of the gaseous atmosphere. Studies on precipitable water by Gunn and East [5] reported the effect of clouds. Considering the presence of all the constituents of the atmosphere together it has been useful to analyse the effect of clouds. Rain is an important hydrometeor when considered along with the effects of water vapour. As a matter of fact, the rain spells are rather occasional as compared to the clouds. Further, the rain is also very much dependent on the location and seasons. Clouds are persistent for longer periods and more common than the rain. But the presence of some of the major components of the atmospheric constituent such as oxygen and water vapour is invariably taken in to account when the total attenuation is calculated in a cloudy situation. Calibration aspects at millimetrewave propagation must incorporate the results of attenuation for the accuracy in observations.

The study reveals that the noise temperature is more informative and useful as compared to attenuation. The attenuation for clear air situation from 10 GHz to 100 GHz varies from 0.0973 dB to 5.1720 dB, on the other hand the attenuation due to cloudy conditions have been found to be from 0.3258 dB to 28.0139 dB. The noise temperature due to cloud has been estimated to be ~135 K at 45 GHz. The effects of water content in cloud and height (thickness) of the cloud on cloud noise temperature have also been discussed in this paper. The estimated change in signal to noise ratio due to cloud, indicates that the change in signal to noise ratio increases considerably from 70 GHz.

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2. Theoretical consideration/statement of the problem

The total attenuation of a radiowave propagating in the medium is due to water vapour, oxygen, cloud, *etc*. The specific attenuation due to water vapour is given by CCIR [6] as follows

$$\gamma_w = \left[0.067 + \frac{2.4}{(f-22.235)^2+6.6} + \frac{7.33}{(f-183.5)^2+5} + \frac{4.4}{(f-323.8)^2+10}\right] f^2 \rho \times 10^{-4} \quad (1)$$

where γ_w is the specific attenuation coefficient due to water vapour in dB/km, f is the frequency in GHz and ρ is the water vapour density in gm/m^3

For calculation of the total attenuation along the slant path, the necessary scale height H can be obtained using the following relation

$$H' = \frac{2H}{\sqrt{\sin^2\theta + \frac{2H}{R}} + \sin\theta} \quad (1a)$$

where R is the earth radius (6370 km) and θ is the angle of elevation of the satellite

Water vapour is not at all a well-mixed constituent of the atmosphere and hence it shows variation due to change of site, season and local meteorological conditions [7]. Also the vertical and horizontal distribution of water vapour varies with space and time

Slobin [8], Staelin [9] presented the values of cloud absorption as a function of temperature and wavelength. An expression for the absorption coefficient α based on Staelin [9] is given by

$$\alpha = \frac{4.343 \times M \times 10^{0.0122(291-T)-1.16}}{\lambda} \text{ dB/km} \quad (2)$$

where M-cloud water particle density g/m^3, T-cloud particle temperature, Kelvins, λ-wavelength, cms

The absorption coefficient as used in radiation transfer calculations is

$$\alpha(\text{Np/km}) = \alpha(\text{dB/km})/4.343 \quad (3)$$

The noise temperature at a given frequency received by an ideal antenna with infinitely narrow beam width looking upward at source outside the atmosphere and ignoring scattering is given by the equation of radiative transfer

$$T_a = T_a' e^{-\tau} + \int_0^\infty T(s)\alpha(s)\left[\exp - \int_0^s \alpha(s')\,ds'\right] ds \quad (4)$$

T_a is effective antenna noise temperature in Kelvins, T_a' is noise temperature of source outside the atmosphere (*e.g.* Black body disc temperature of Sun, moon or cosmic backgrounds) in Kelvins, $T(s)$ is physical Temperature of a point s in the atmosphere in Kelvins, τ is total atmospheric attenuation (Optical depth) in Np (Nepers), $\alpha(s)$ is total atmospheric attenuation at point s in the atmosphere, s is distance from the antenna to a point in the atmosphere in km

The total absorption coefficient $\alpha(s)$ is the sum of the individual coefficients of all the atmospheric constituents. The loss through the entire atmosphere is

$$L(\text{ratio}) = e^{\tau} = \exp\int_0^\infty \alpha(s')\,ds',$$

L is the loss through the entire atmosphere and τ is the optical depth in Nepers

The attennuation due to a single constituent is

$$A_{\text{total}}(\text{dB}) = \int_0^\infty \alpha(z)\,dz = \alpha_0 z_0, \quad (6)$$

where α_0 is the surface attenuation coefficient in decibels per km and Z_0 is the scale height for absorption, in kms

Knowing the surface attenuation of water vapour, oxygen and cloud, and then using their respective scale heights, the total attenuation is deduced. Thus, the total attenuation is alternatively given by

$$L = \sum \alpha_0 Z_0$$

In this paper scale height of 5.4 km for oxygen and 3 km for cloud have been used. But total attenuation due to water vapour has been obtained by the model represented by eq (1) and along the zenith the necessary scale height with correction factor applied using eq (1a)

For a homogenous, isothermal atmosphere, $\alpha(s) = \alpha$, the mean absorption coefficient and $T(s) = T_p$, the physical temperature at a point in the atmosphere

For a narrow antenna beam which keeps the source away from the receiver, the equation of radiative transfer becomes (assuming $T_a' = 0$)

$$T_a = T_p \alpha \int_0^l e^{-\alpha s}\,ds,$$

where l is the top of the atmosphere

$$T_a = T_p(1 - e^{-\alpha l}), \quad (8)$$

$$T_a = T_p\left(1 - \frac{1}{L}\right) \quad (9)$$

Variation of attenuation due to main constituents (oxygen and water vapour) has been shown in the work of Jacob and Stacey [10], to be approximately proportional to density. Dependence of attenuation with height in turn, is given by

$$\alpha(z) = \alpha_0 e^{-z/\zeta}, \tag{10}$$

where α_0 is the surface attenuation coefficient, in dB/km and ζ is the scale height for attenuation in kms as usual.

The total attenuation thus is the sum of significant or measurable contributions from the atmospheric constituents obtained using eq. (7). The models used for each of the contributors like water vapour and cloud, are fairly established; have been used directly. Eqs. (1) and (2) give the specific attenuation; also, the scale heights for each of these in the mid-latitudes are 2 km and 3 km (for the worst condition ρ [illegible] 1 gm m^{-3}) respectively. For the oxygen component the well-accepted values of CCIR Reports Recommendations [6] have been used for the estimation of the total attenuation using scale height of 5.4 km.

Evidently, the total attenuation was calculated and the order of the noise temperature so obtained was also compared with the observed values of the brightness temperature recorded by the remote sensing organisations. It has been observed to be very close after deducting the ground effect which itself is satisfactory. Further, the comparison of the radiative transfer results and with approximation calculations have also been dealt in Slobin [8]. They differ marginally. Even in the real atmospheric situation the noise temperature shows similar dependence on the mean physical temperature of the constituents near the scale height and the total loss factor (L). The analytical results are presented in comparison with the simple approximation in the following section.

Again applying the same condition of a narrow antenna beam that keeps the source away from the receiver. Equation of radiative transfer becomes (assuming $T_a' = 0$)

$$T_a = \int_0^{\infty} T(s)\alpha(s)\left[\exp - \int_0^{s} \alpha(s')ds'\right] \tag{11}$$

The calculation of T from the above expression is still cumbersome, even with the use of computers. This is mainly due to the double integral form of the equation. We make the calculation easier without loss of generality and realistic condition.

We take

$$T(s) = T_0 \exp^{-\chi s}, \tag{12}$$

where $\chi = \dfrac{R\beta}{H_\rho g}$ = 0.0278 (at Kolkata), using β is the lapse rate R is the gas constant H_ρ is the scale height for hydrostatic pressure and g is the acceleration due to gravity.

Eq. (11) then reduces to a much simpler form using the above relations (10) and (12)

$$T_a = T_0 \int \alpha_{0t} \ [illegible]$$

$$T_0\alpha_t \int e^{\ [illegible]}\ dz$$

Substituting [illegible] $= u$, we get

$$T_a = \alpha_0 T_0 Z_t \int e^{\ [illegible]}\ du$$

Now substituting

$$T_a = \alpha_0 T_t Z_0 [illegible]$$

Again, substituting $v = \alpha_0 Z_0 t$,

$$T = \frac{T_0 \ [illegible]}{(\alpha_{0t})^2} \int [illegible]\ dv$$

Thus the integration with v would give the following result

$$T = T_0 \left[1 + [illegible] \right] [illegible]$$

$$\frac{T(n+1)}{A_t^n} \left[1 - \frac{1}{L} \right] \tag{13}$$

Now it is easy to see that the gamma function part is negligible due to obvious reasons of n-value and the denominator. Also, it is observed that [illegible] 1, for the frequency more than 15 GHz as has been observed from the calculated values of (A_t = [illegible] total attenuation due to the atmosphere) and $T_p = T_0 e^{\ [illegible]}$. Applying the above constants the equation takes the form

$$T_a = T_0 \left[1 - [illegible] \right] \left[1 - \frac{1}{L} \right] \tag{13a}$$

which approximates to

$$T_a = T_p \left[1 [illegible] \right] \tag{14}$$

It is worthwhile to see that it assumes the same form as (9), which substantiates the well-drawn conclusion.

The loss factor for each constituent then may be found from

$$L(\text{ratio}) = 10^{[\alpha_{total}(dB)]/10} \tag{15}$$

Cloud temperatures have been estimated by using the surface temperature and the lapse rate (6.5 K/km).

3. Cloud types and properties

Cloud consists of liquid water particles having diameters from about 1 micron (μm) to as much as 400 microns (μm) [11]. For comparison raindrops have size distributions from 100 μm (0.1 mm) to 5 mm. Clouds are not water vapour (which is clear, colourless gas), although relative humidity is nearly 100% within cloud. Clouds can exist at high temperatures + 20 °C as well temperature below freezing point at −10°C. High level clouds such as cirrus, are composed of ice crystals and are not generally found at temperatures above 1° C [12]. Ice clouds do not contribute substantially to microwave attenuation (though they may lead to depolarization). A particular cloud type will have a range of water particle sizes. Fair-cumulus clouds have particles with diameters from 4 to 15 μm, cumulonimbus clouds have particle diameters from 2 up to 100 μm, where the distinction between cloud particles and suspended rain is not clear. Typical model cloud drop size spectra (number of particles *versus* diameter) for numerous cloud types are shown in the work of Carrier *et al* [13]. For a justifiable analysis of the clouds, we use the most recent results of the Liebe's Model [14] used in collecting the NOAA data, and according to the Liebe's model, Table 1 presents the cloud properties over Kolkata. This also has been found to be true in mid latitudes [15]. The variations as depicted in the tabulated results using this model have been incorporated to see the resultant effect due to the range of variation. Further, the observed changes in the noise temperature analysis with the parametric changes give some conclusive results about the characteristics of the cloud under study.

Table 1. Cloud properties over Calcutta

Cloud Type	M (g/m³)	Cloud Bottom	Height (m) Top
Cumulus	1.96	610	2700
Altostratus	0.41	2400	2900
Strato cumulus	0.55	660	1320
Nimbo-stratus	0.61	160	1000
Stratus	0.4	160	660
Stratus	0.22	130	1000
Stratus-Stratocumulus	0.15	660	2000
Strato-cumulus	0.30	660	2000
Nimbo-stratus	0.65	160	660
Cumulus-cumulus	0.57	660	2700
Cumulus		660	3400

(After Falcone and Abreu [15])

The emphasis has been laid on some directly deducible properties of the cloud, while using for microwave communication purpose. In order to elucidate this aspect, the effect of the cloud mass density and cloud height

The observed range of variation has been used to estimate the change in noise temperature at a desired frequency of operation.

The attenuation and noise temperature effects of cloud in microwave frequency band lead to degradation in the performance of radio systems. If the noise temperature is assumed to be T_{new} for the cloudy condition and T_{base} is the noise temperature for clear air condition and δA is the difference of attenuation due to cloud and clear air then the change in signal to noise ratio (ΔSNR) is given by

$$\Delta SNR = 10 \log_{10}\left[\frac{T_{new}}{T_{base}}\right] + \delta A$$

4. Results and discussion

The attenuation due to the clear air atmosphere and also cloudy conditions for the operational frequencies in the range from 10 GHz to 100 GHz have been deduced and presented in Figures 1(a) and 2(a). Attempt has been made to relate the

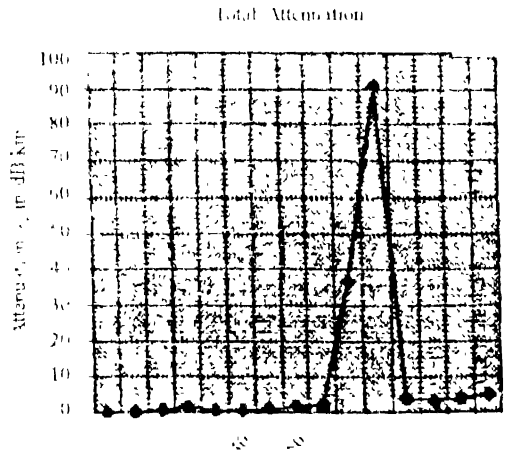

Figure 1(a). Variation of attenuation with frequency of the microwave in clear air condition

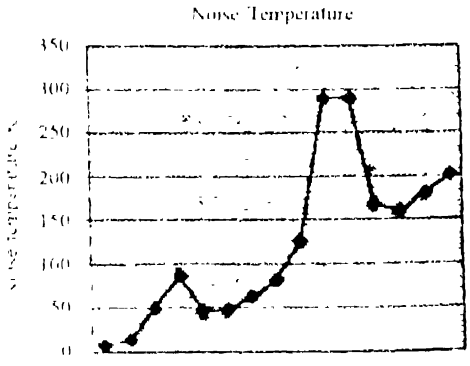

Figure 1(b). Variation of noise temperature with frequency of the microwave in clear condition results so obtained to use the proper frequency of the microwave for the study of cloud characteristics The total microwave attenuation is the sum of the attenuation due to water vapour and oxygen for clear air condition For cloudy conditions, there is an additional attenuation term due to cloud However, it has been observed that the noise temperature is more informative and useful for study of characteristics of the constituents of the atmosphere than the attenuation. It is seen in Figure 1 that the maximum attenuation is observed at 60 GHz is due to oxygen component For operating frequencies between 50 GHz and 70 GHz there is

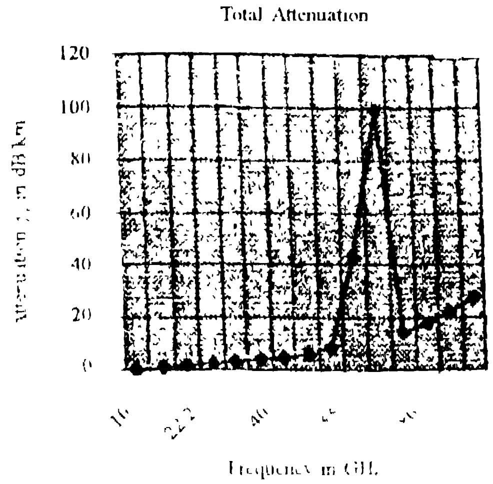

Figure 2(a). Variation of attenuation with frequency for cloudy condition

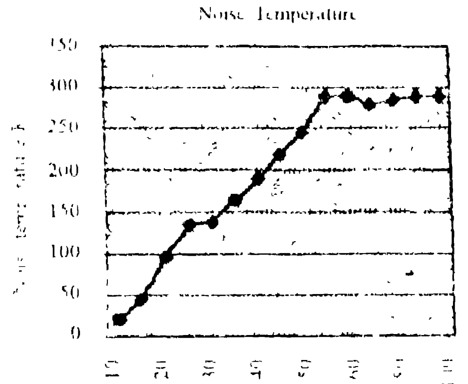

Figure 2(b) Variation of noise temperature with frequency for cloudy condition

marked increase in the attenuation with a maximum at 60 GHz for the characteristic line of oxygen But in the estimation and analysis, the noise temperatures have been found much more advantageous than the attenuation The atmospheric noise temperatures deduced for clear air situation and cloudy condition are presented in Figures 1(b) and 2(b) It is seen in these figures that the noise temperature under clear air condition between 10 GHz and 100 GHz varies abruptly at different frequencies while under clouds condition the variation of noise temperature is systematic from 10 GHz to 80 GHz The noise temperature is around 285 K from 80 GHz to 100 GHz. Since the characteristic of variation of noise temperature clearly indicates that certain frequencies in the range of operation are really energy consuming and results in radiation losses due to absorption of the major constituents of the earth's atmosphere Particularly, the losses due to water vapour and oxygen give rise to increase in noise temperature and peaks at frequencies of 22.235 GHz and 60 GHz respectively (Figure 1b)

The noise temperature due to cloud, which is the difference of noise temperature under cloudy condition and clear air situation in the present study has also been determined and presented in Figure 3 It has been estimated that the noise

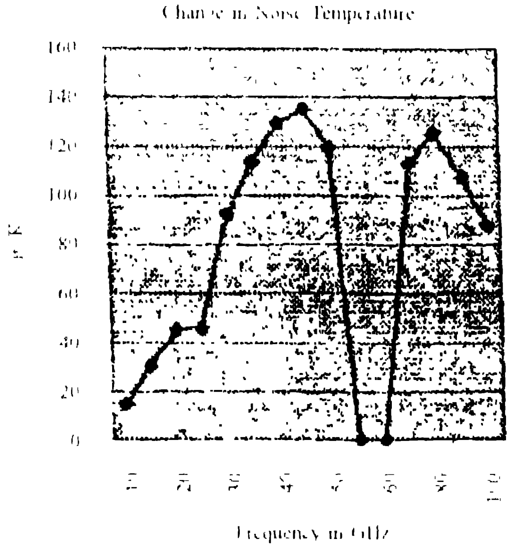

Figure 3 Change in noise temperature variation with frequency due to clouds relative to clear air situation

temperatures due to cloud at 45 GHz and 80 GHz are 135 K and 125 K respectively which are maximum values in the frequency range from 10 GHz to 100 GHz The noise temperatures due to cloud at 55 GHz and 60 GHz are 0.05 K and 0 K It is also seen in Figure 3 that the noise temperature due to cloud increases from 10 GHz to 45 GHz and two minima are found at 55 GHz and 60 GHz The noise temperature due to cloud at 70 GHz is around 112 K and having a second maxima at 80 GHz with 125 K The noise temperature due to cloud starts decreasing from 80 GHz as seen in Figure 3 The frequency 45 GHz is most ideal for cloud related studies since the maximum noise temperature due to cloud is observed at this frequency

It has been seen that the liquid water content in the cloud varies from 0.1 gm/m^3 to 1 gm/m^3 The noise temperature due to cloud having cloud height 3 km has been determined at 45 GHz for various water contents in the cloud and the results have been presented in Figure 4. It is seen that the noise temperature due to cloud increase exponentially. The

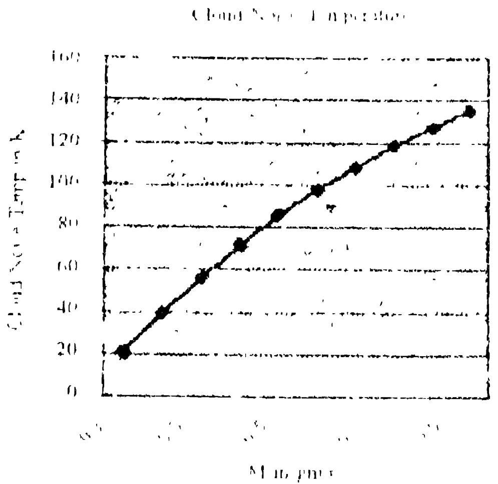

Figure 4 Variation of noise temperature due to cloud at operating frequency of 45 GHz with mass density of cloud

cloud noise temperature at 1 gm/m³ is nearly about 135 K, while at 0.5 gm/m³, it is around 85 K at 45 GHz.

It has been seen that the noise temperature due to cloud depends strongly on the thickness of the cloud. Also the cloud noise temperature increases exponentially with cloud

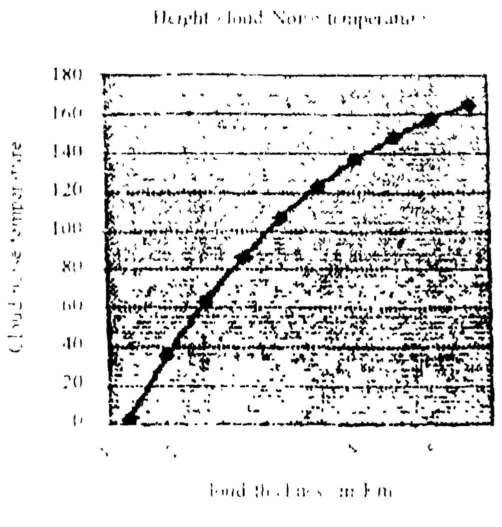

Figure 5 Variation of noise temperature due to clouds with respect to the clear air condition at operational frequency of 45 GHz with cloud

thickness (Figure 5). The cloud noise temperature for 5 km cloud thickness is found to be 165 K while at 1 km the cloud noise temperature is 5 K.

The attenuation and noise temperature due to clouds lead to serious degradation in the performance especially for satellite borne low noise microwave radio systems. It is therefore essential to derive the results on change of signal to noise ratio at different frequencies. The change in signal to noise ratio is estimated by eq (16). The change in signal

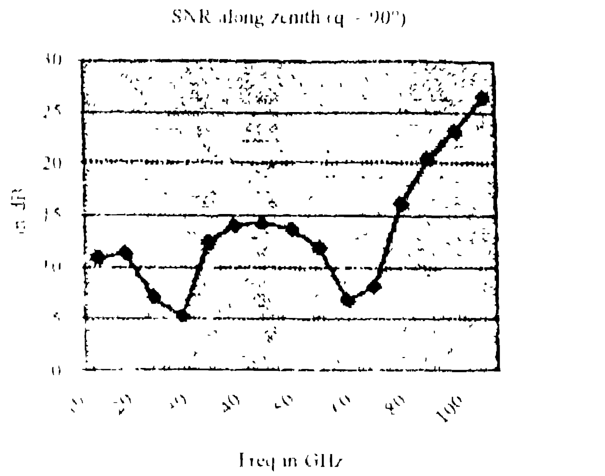

Figure 6 Signal-to-noise ratio variation with frequency for the cloud condition in relation to clear air situation

to noise ratio is appreciable upto 55 GHz and such is due to major contribution from cloud noise temperature while the large changes in signal to noise temperature from 60 GHz is mainly due to the contribution of attenuation due to clouds (Figure 6).

Acknowledgments

The reported study is a part of the project work sponsored by the Department of Science & Technology (DST), Government of India, New Delhi. The support provided by the DST is gratefully acknowledged.

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